Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL081703

Key Points:
- A new plate reconstruction of East Asia fully depicts the NE migration of a trench-trench-trench triple junction since 30 Ma
- This triple-junction migration led to the overlapping, tearing, and detachment of subducted slabs in East Asia
- Large–scale ambient mantle flow should have contributed to the formation of the horizontal slab

Supporting Information:
- Supporting Information S1

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Citation:
Ma, P., Liu, S., Gurnis, M., & Zhang, B. (2019). Slab horizontal subduction and slab tearing beneath East Asia. *Geophysical Research Letters*, *46*, 5161–5169. https://doi.org/10.1029/2018GL081703

Received 15 DEC 2018
Accepted 25 APR 2019
Accepted article online 29 APR 2019
Published online 21 MAY 2019

Slab Horizontal Subduction and Slab Tearing Beneath East Asia

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Abstract The present-day architecture of subducted slabs in the mantle as inferred from seismic tomography is a record of plate tectonics through geological time. The unusually large slab that lies nearly horizontally above the 660-km mantle discontinuity beneath East Asia is presumably from subduction of the Pacific plate. Numerical models have been used to explore the mechanical and geophysical factors that contribute to slab stagnation, but the evolution of this horizontal structure is not fully understood because of uncertainties in the plate-tectonic history and mantle heterogeneity. Here we show that forward mantle-flow models constrained by updated tectonic reconstructions can essentially fit major features in the seismic tomography beneath East Asia. Specifically, significant tearing propagated through the subducted western Pacific slab as the Philippine Sea plate rotated clockwise during the Miocene, leading to internal slab segmentation. We believe this tearing associated with Philippine Sea plate rotation also affects the horizontal configuration of slabs.

Plain Language Summary The present-day architecture of subducted slabs in the mantle as inferred from seismic tomography is a record of plate tectonics through geological time. The structure of the mantle below East Asia is dominated by a flat slab which extends more than 2,300 km laterally inland (Liu, Zhao, et al., 2017, https://doi.org/10.1016/j.epsl.2017.02.024, https://doi.org/10.1016/j.earscirev.2017.10.012). The origin of this unusual but globally significant flat-slab structure has been the subject of considerable discussion in the literature through a series of global and high-resolution seismic inversions. Is this phenomenon caused by unusual regional processes, or have some global mantle processes been overlooked? Here we reproduce this highly unusual flat-slab structure with a four-dimensional computational model and argue that this slab is a natural consequence of the plate-tectonic evolution of East Asia. We provide a solution to this problem through a combination of new plate-tectonic reconstructions and a 4-D computational approach that assimilates plate tectonics with the physics of mantle convection. This paper reports a new paradigm for the East Asia margin, where the regional tectonics are characterized by the development of a typical trench-trench-trench triple junction, and resultant significant tearing that propagated through the subducted western Pacific slab as the Philippine Sea plate rotated clockwise during the Miocene.

1. Introduction

East Asia has experienced long-term subduction since the Mesozoic (Isozaki et al., 2010). The current tectonic configuration of this region is marked by the development of a typical trench-trench-trench (TTT) triple junction where the Pacific plate, Eurasian plate, and Philippine Sea plate join (Figure 1). At the southern part of the triple junction, the PSP is moving northwestward, with a pole near Hokkaido (Seno et al., 1993). The mantle structure beneath East Asia is characterized by a horizontal slab that lies above the 660-km discontinuity. The Cenozoic tectonic history has been reconstructed through a variety of observations. Despite kinematic uncertainties, most PSP models generally agree on the northward motion of this plate from equatorial latitudes with clockwise rotation (Haston & Fuller, 1991). However, the linkages between the regional plate-tectonic history in a global context, slab evolution, and mantle heterogeneities have remained elusive. Here we formulate a series of 4-D geodynamic models with assimilation of the newly constructed tectonic history to reproduce the distinctive present-day mantle structure beneath eastern Asia.

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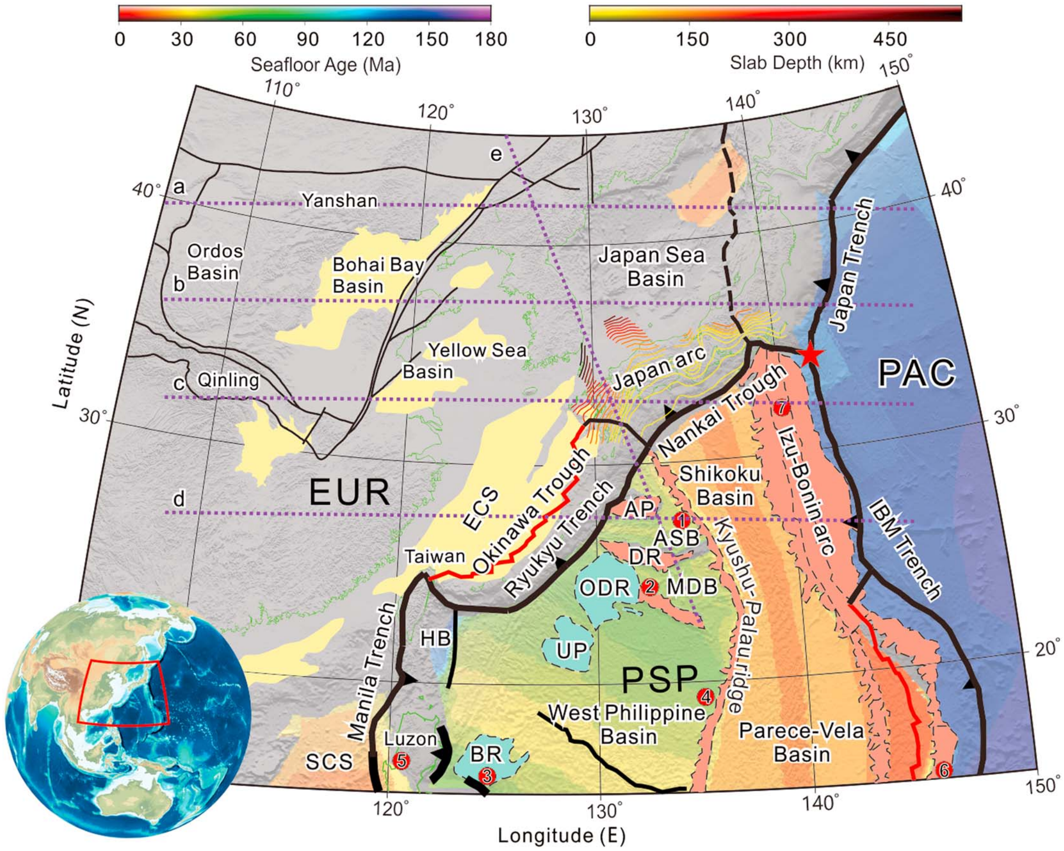

Figure 1. Structural map of East Asia. The seafloor crust ages of oceanic basins are rendered according to a global age model (Zahirovic et al., 2016). The details of the Philippine Sea slab that is subducting beneath SW Japan were adopted from Asamori and Zhao (2015) and are colored by depth. Cenozoic rifting basins are depicted as white-yellow regions, and regional faults are depicted as thin black lines in the gray-colored continental crust. The thick black lines with a sawtooth shape represent subduction zones, with the sawtooth points directed toward the overriding plate. The thick red lines denote rifting and seafloor spreading centers. Coastlines are drawn with light-green lines. The purple dotted lines across the region indicate the locations of selected profiles (a–e). The brick-red polygons represent arcs and relic arcs in the PSP. The light-green polygons delineate ocean-island basalt. The red star highlights the Boso Triple Junction. The numbers 1–7 in red circles represent drilling and paleomagnetic sampling sites. 1 = IODP U1438; 2 = DSDP 446; 3 = ODP 1201; 4 = Luzon; 5 = DSDP 292; 6 = Saipan; 7 = Izu-Bonin. PAC = Pacific plate; EUR = Eurasia plate; PSPhilippine Sea plate; IBM = Izu-Bonin-Mariana trench; Huatung basin; CBSC = Central basin spreading center; SCS = South China Sea basin; ECS = East China Sea shelf basin; ASB = Amami-Sankaku basin; MDB = Minami-Daito basin; AP = Amami Plateau; DR = Daito Ridge; ODR = Oki-Daito Rise; UP = Urdaneta Plateau; BR = Benham Rise.

2. Methodology

2.1. Plate Reconstruction With GPlates

We modified a recently published global reconstruction (Zahirovic et al., 2016) with GPlates (www.gplates.org), which incorporated compiled global seafloor-spreading histories with a hybrid reference framework to tie the global tectonic system with an underlying mantle. Our reconstruction combined geological and geophysical observations from East Asia margin (supporting information Table S1) to fully depict the evolving plate boundaries and plate kinematics. Digital plate boundaries, reconstructed seafloor-age distributions, and dynamic topological polygons were jointly created at 1-Myr time intervals. Paleomagnetic data, hot spot signature, and arc volcanism were accounted for in the reconstruction. We adopted the motion history of PSP described by Deschamps and Lallemand (2002) from 50 to 35 Ma, which considered both the onshore geology and the PSP's spreading direction at its earliest stage. Onshore geology along the East Asia margin provided constraints for the PSP's motion from 35 to 16 Ma. We determined the PSP's position at 15 Ma by calibration with the interpreted position of the Izu-Bonin-Mariana trench (IBM) from 609-km-depth slice of the global tomography model MIT-P08. In SW Japan, the change from oblique subduction of the PSP to northwestward orthogonal subduction at the end of the Miocene was reconstructed based on the onshore geology there. The paleo-position of the PSP was derived by assuming that the plate has been moving at its current speed since 6 Ma. A comparison of the predicted paleo-latitude and declination data with paleomagnetic data suggests that the kinematic model generally fit with published paleomagnetic data around the PSP (Figure S1).

2.2. Assimilating Mantle Convection and Slab History

Time-dependent global mantle-convection models were computed with the CitcomS package (Zhong et al., 2008) by solving the thermal-convection problem of incompressible fluid in a spherical shell with the finite element method. These models were constrained by the tectonic history with a variety of boundary and initial conditions. Kinematics extracted from GPlates for every million years were used as the velocity boundary conditions on the surface. Evolving lithosphere and one-sided subducted slabs above 350-km depth created based on the reconstruction and geophysical observations were progressively assimilated in one-million-year increments (Bower et al., 2015). The thermal structure of the oceanic lithosphere was derived from the reconstructed seafloor age according to a half-space cooling model. The thermal field of the global continent lithosphere relied on its tectono-thermal age. Similar to the boundary conditions, the initial temperature field was reconstruction-based (see Supporting Information S1 for more details). All the implementations ensured a general agreement between the predicted buoyancy distribution in the mantle and geophysical observations and helped build a fundamental platform to assess alternative plate models and associated geodynamic scenarios (Zahirovic et al., 2016).

3. 4-D Geodynamic Modeling of Plate-Mantle Coupling

3.1. Results of Plate Reconstruction

Results of new reconstruction are shown in Figure 2. Following the Izanagi plate's subduction during the Mesozoic (Liu, Gurnis, et al., 2017, https://doi.org/10.1016/j.earscirev.2017.10.012), the Izanagi-Pacific mid-ocean ridge arrived at the East Asia continent margin in a subparallel manner at approximately 55 Ma, eliminating some slab pull on the Pacific while putatively triggering global-scale tectonic reorganization (Seton et al., 2015). During this period, the PSP was still in its infant stage and was located near the equator at a back-arc position, overriding south-dipping Pacific subduction (Figure 2a). Crust extension due to the slab-rollback and the thermal rejuvenation of the Philippine relic arc could have caused a large age and buoyancy contrast and led to the onset of Izu-Bonin subduction at approximately 52 Ma (Leng & Gurnis, 2015). Later, short-lived hot spots and mantle upwelling triggered propagating rifts in the western central basin spreading ridge of the west Philippine basin and excess volcanism at the Urdaneta Plateau, Oki-Daito Rise, and Benham Rise (Deschamps et al., 2008; Ishizuka et al., 2013; Figures 1 and 2b).

Further west, South China Sea (SCS) spreading started at ca. 32 Ma, possibly driven by slab pull that was exerted by the southeast-dipping subduction of the Mesozoic proto-SCS (Zahirovic et al., 2016; Figure 2c). At ca. 30 Ma, the Shikoku and Parece-Vela basins started spreading on the proto IBM arc, leaving the abandoned Kyushu-Palau ridge lying across the middle of the PSP. After the extinction of the proto-SCS, the SCS basin was subducted in an eastward direction beneath the PSP along the Manila trench at ca. 22 Ma (Yumul et al., 2003).

Latest Oligocene to earliest Miocene may be the time when oblique convergence between PSP and the Eurasian continent initiated, as evidenced by basin inversions in the East China Sea shelf basin (Su et al., 2014) and shortening at 20 Ma along the Japan margin (Raimbourg et al., 2017; Figure 2c). The PSP continued to move northward, and its subduction beneath eastern Asia propagated diachronously along the Ryukyu trench. The ongoing roll-back of the Pacific plate, extrusion of the NE Japan arc, and northward convergence of the PSP during the Early Miocene induced the opening of the Japan Sea basin and the associated rotation of the Japan arcs (Otofuji, 1996; Figures 2d and S2). The clockwise rotation of the SW Japan arc resulted in its obduction onto the Shikoku basin crust, accompanied by a burst of a variety of volcanism across the arc (Kimura et al., 2014).

A hiatus in the PSP's subduction occurred during the Late Miocene, which was accompanied by a lack of subduction-related volcanism from 10 to 6 Ma in the SW Japan (Mahony et al., 2011; Figure 2e). The PSP's subduction resumed and the rifting of the Okinawa trough reached its most extensive phase during the Pliocene (Figure S2; Sibuet et al., 1995). In the southern section of the Ryukyu arc, the Luzon arc began to obliquely intrude into the northern SCS passive margin during the Late Miocene (Kong et al., 2000),

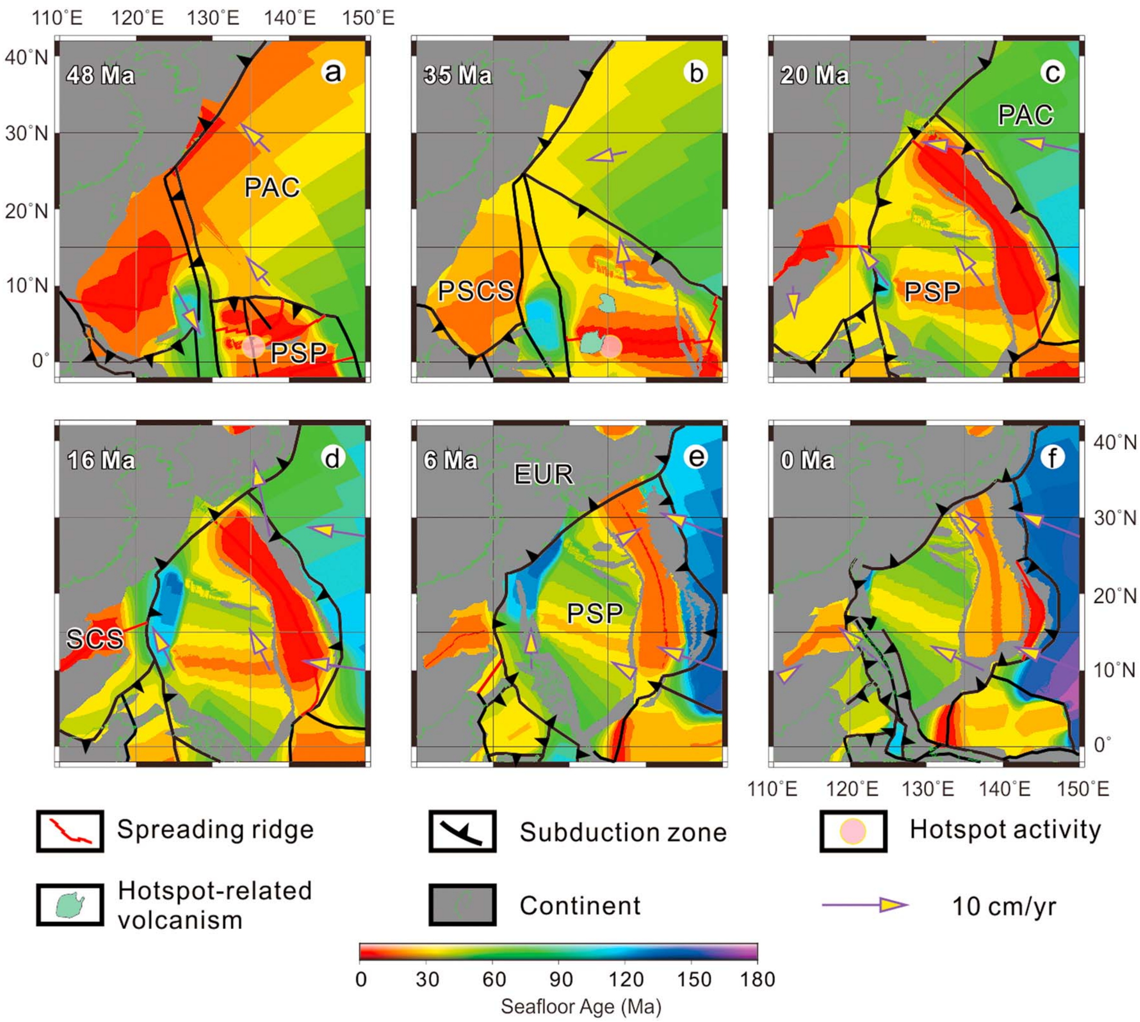

Figure 2. New tectonic reconstructions of East Asia with colored seafloor ages and kinematics. (a) 48 Ma. The PSP was located near the equator. Its juxtaposition with the Pacific crust caused initial subduction in the proto Izu-Bonin zone. (b) 35 Ma. The PSP continued to migrate northward. The trench-trench-trench triple junction began to form along the East Asian margin. (c) 20 Ma. Back-arc spreading created the Shikoku and Parece-Vela basins behind the Izu-Bonin-Mariana trench. The young Shikoku basin crust first left a record on the SW Japan arc. (d) 16 Ma. The triple junction continued to migrate northeastward, leaving unusual magmatic assemblages at the SW Japan arc in the mid-Miocene. (e) 6 Ma. The triple junction might have reached its present position. The PSP changed its direction of motion and subducted orthogonally beneath East Asia. (f) 0 Ma. The rollback of the PSP slab and NW wedging of the PSP led to the asymmetric rifting of the Okinawa trough and the mountain building of the Taiwan orogeny. The other symbols are the same as those in Figure 1. PSCS = Paleo-South China Sea basin.

resulting in the subduction of Eurasia continental crust beneath the PSP and the creation of the Taiwan orogeny (Figure 2f).

Previous tomography-based reconstructions of Southeast Asia provided different histories. In the reconstruction by Wu et al. (2016), a putative large marginal basin (East Asia Sea) was separated from the Pacific plate by strike-slip faults and subduction zones and later consumed by the growing PSP. A stage that involved the double dipping subduction of the Pacific plate before the collision of the PSP with Eurasia was proposed. In another reconstruction, in which the paleo-position of the Izu-Bonin trench was mainly determined from tomography models through a simple transformation between depth and geological age, the triple junction had arrived at its present position before 35 Ma (Zahirovic et al., 2016), which is quite different from our new reconstruction.

3.2. Results of 4-D Data-Assimilation Geodynamic Modeling

The reconstruction by Zahirovic et al. (2016) avoided the essential question as to why large horizontal slabs exist below East Asia and whether the existence of these slabs suggests normal mantle processes or processes that are regionally unique. To overcome these limitations, we used a physics-based mantle-flow approach with reasonable mantle viscosities, phase relationships, and boundary conditions (Figure S3), where tectonic events and associated mantle evolution were explored by assimilating reconstructed tectonics into global geodynamic models (Bower et al., 2015; see Supporting Information S1 for more details). We created a series of global flow models with different parameter settings (Table S2). The new reconstruction was used for cases 1-1 to 1-6, while the previous reconstruction from Zahirovic et al. (2016) was used for case 2-1. Although the model is global, we only show the results around East Asia in the following sections.

Models (cases 1-1, 1-2, and 2-1) were evaluated via a comparison of predicted present-day structure against the seismic tomography along four EW profiles across eastern Asia (Figure 3). Through central Japan, case 1-1 (magenta lines) predicted a horizontal slab within the mantle transition zone, although the Pacific slab turned into the lower mantle and failed to reach as far inside the continent as inferred tomographically (profile a). Slightly southward (profile b), the slab showed a weaker tendency of defection at its leading edge, appearing as a long horizontal slab that fit the tomography images. In profiles across the northern PSP to the south of the triple junction, the predictions matched the tomography within the transition zone and beneath the Ryukyu trench (profiles c and d). Beneath Kyushu, the predicted slab was segmented and may correspond to the necking of the high-velocity anomalies in the seismic images (profile c). In profile d, the predicted Izu-Bonin slab was shorter than what was indicated in the tomographic image. On the Eurasian side, the flow model predicted a short slab beneath the East China Sea shelf basin, with the Ryukyu slab resting above the horizontal Pacific slab (Figure 3c). In the lower mantle, a gap between the deepest Izanagi slab and the horizontal slab is predicted, which may have resulted from the subduction of the Izanagi-Pacific ridge (Honda, 2016, 2017). Interestingly, the deepest slab is clearly offset from the high-velocity anomalies in the tomography images along the northern profiles. This may be related to uncertainties in the Mesozoic plate kinematics, intracontinental deformation, and viscosity profile. Overall, case 1-1, which had a more reasonable subduction duration, generally provided a good fit with the tomographic images, including those of the high-resolution regional tomography model FWEA18 (Tao et al., 2018; Figure S4).

Case 1-2 (orange lines) created a definitive horizontal slab geometry without any downward deflection into the lower mantle because of the absence of the Izanagi slab in the lower mantle. Nevertheless, this case exhibited a similar evolution to case 1-1 (Figure S5). Case 2-1 (green lines) had poorer agreement than that of case 1 with the seismic images (Figures 3 and S6). Long-term anchored Izu-Bonin subduction caused the slab to penetrate into the lower mantle. Additionally, the transient northeastward deviation of the TTT triple junction outside northeastern Honshu at 7 Ma resulted in the huge slab wall in profile b, east of the clear seismicity (Figures 3 and S6). The different outcomes of cases 2-1 and 1-1 suggest the necessity of a retreating TTT triple junction after the Oligocene along the East Asian margin rather than before 35 Ma. The predicted results for cases 1-3 to 1-6 were similar to those for case 1-1 (Figure S7), implying that reasonable tectonic reconstructions and slab assimilation are the dominant control in 4-D data assimilation modeling.

4. Discussion

The good fit between the geodynamic predictions and seismic images and between the slab history and geological events provides insight into the 4-D geodynamics of East Asia. Since ca. 55 Ma, Pacific-plate subduction has dominated the East Asian margin. The clockwise rotation of the PSP and northeastward migration of the triple junction along the East Asian margin caused the replacement of the Pacific-plate subduction beneath Kyushu with PSP subduction and produced a series of deep structures (Figures 4 and 5). A subvertical tear propagated near the TTT triple junction, dividing the subducting Pacific crust into one slab along Japan and one along IBM (Figure 5). Along the southwestern branch of the TTT triple junction, the subduction of the Pacific plate was terminated by the approach of the PSP. Meanwhile, the Pacific slab could have been detached by a major subhorizontal tear, which could have propagated from the Ryukyu trench to the Nankai trough (Wortel et al., 2009; Figure 5). As the triple junction migrated, the complete detachment of the Pacific slab beneath the Ryukyu trench during the Late Miocene finally produced segmentation in the horizontal slabs within the mantle transition zone (Figure 4). During the clockwise rotation of the PSP, the undetached Pacific slab could have prevented the weak Shikoku slab from laterally migrating northeastward beneath the Nankai Trough and forced the slab to deform while leaving an offset between the surface projection of the Shikoku window and the remnant spreading ridge of the Shikoku basin (Figure 1).

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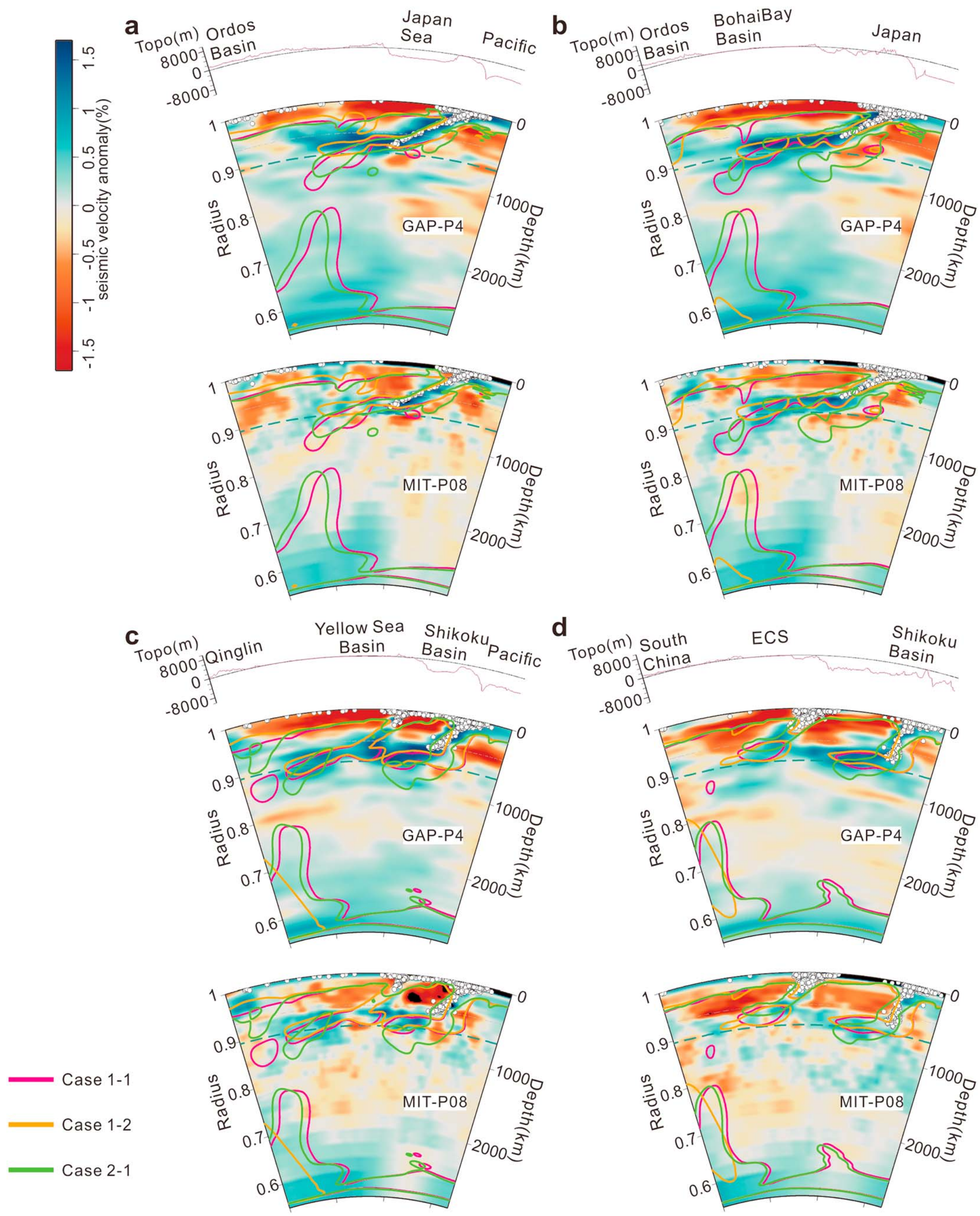

Figure 3. Comparison between the predicted slab structures in case 1-1 (magenta lines), case 1-2 (orange lines), and case 2-1 (green lines) and the global seismic-tomography models GAP-P4 and MIT-P08 along profiles (a) to (d) (see Figure 1). For each profile, slabs are delineated by temperature contours that are 10% lower than the ambient mantle temperature, which could roughly correspond to a high-velocity anomaly of 0.8% in the tomography images. The corresponding global high-resolution *P* wave model images from MIT-P08 (arranged in the lower position) and GAP-P4 (arranged in the upper position) were plotted as background. The NEIC (National Earthquake Information Center) seismicity from 1 January 2010 to 19 February 2017 within 100 km on each side of the profile is shown as small, white circles. The top profile shows the topography information. The profile locations are shown in Figure 1; the other symbols are the same as those in Figure 1.

Since the flow models managed to reproduce the horizontal Pacific slab in the mantle transition zone beneath east Asia, we labeled and tracked particles (tracers) within Japan and proto Ryukyu slabs in case 1-1 to assess the temporal migration of materials of the horizontal slab (Figure S8). The analysis suggests the stagnant age, when the horizontal slab entered the mantle transitional zone, beneath the Bohai Bay

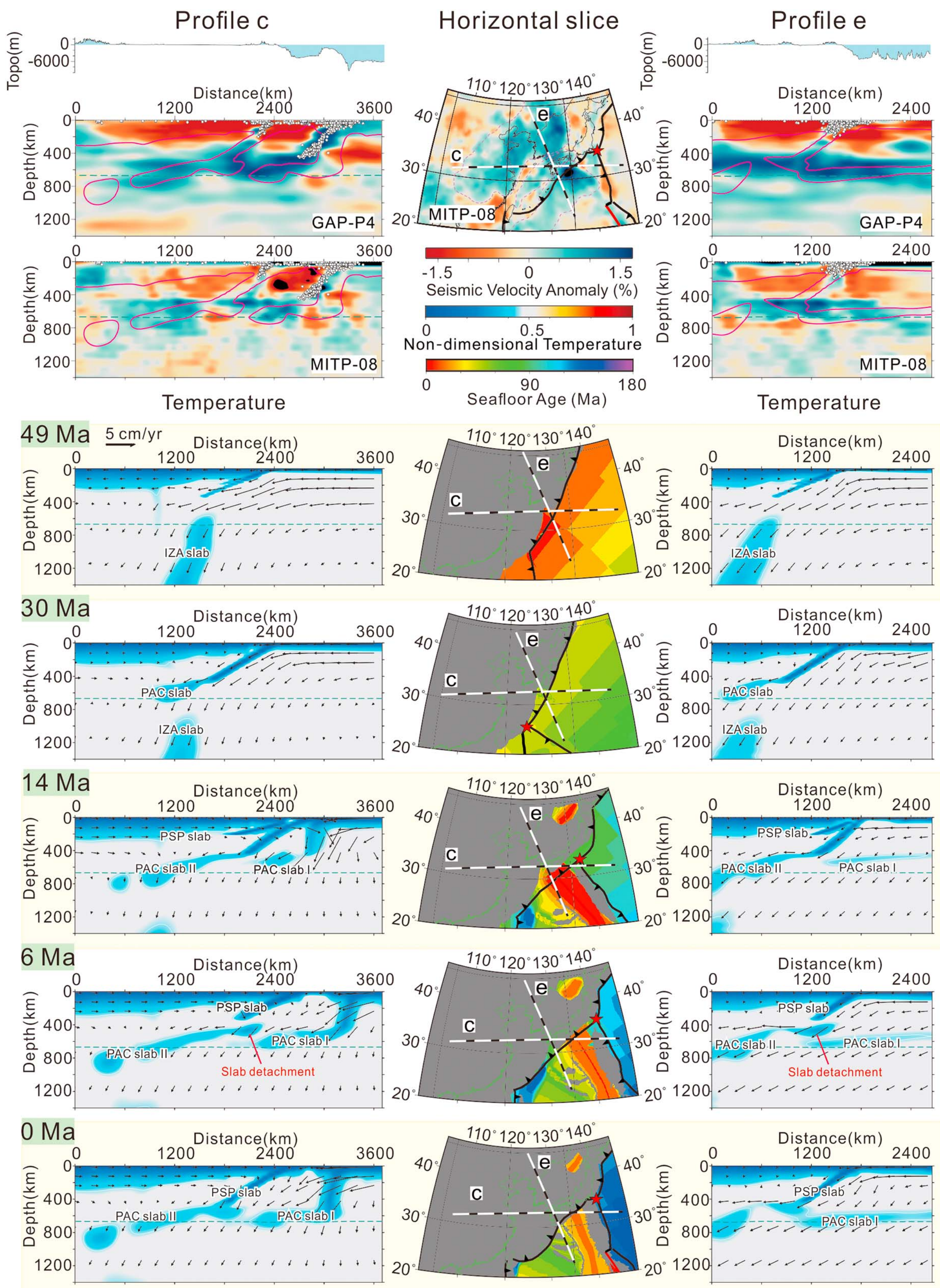

Figure 4. Temporal evolution of subducted slabs along profiles c (left column) and e (right column) with reconstruction (middle column) in case 1-1. The segmented slabs that are associated with the migrating-trench model are compared with seismic tomography images in both vertical (left and right columns) and horizontal slices (middle column) for mutual identification. All the symbols are the same as those in Figures 2 and 3. The locations of the profiles are shown in Figure 1.

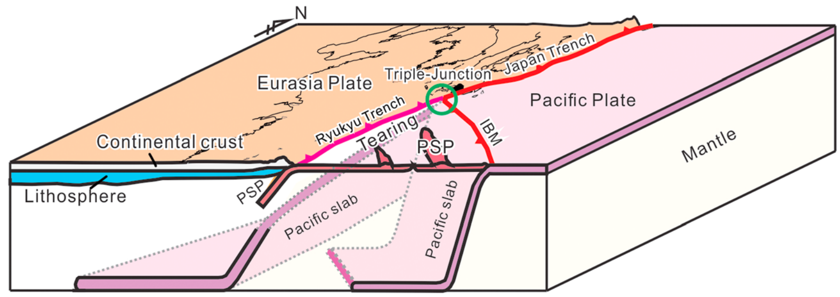

Figure 5. Conceptual model that shows the geodynamic process that is associated with the migrating triple junction. The lateral tearing of the Pacific slab propagated along the East Asian margin at the triple junction. While the Pacific slab was detached along the Ryukyu trench, the Philippine slab was gradually subducting. The torn Pacific slabs subducted into the mantle transition zone. The other symbols are the same as those in Figure 1.

basin is approximately 40 Ma, and the maximum stagnant age of the slab beneath the northern PSP is approximately 20 Ma.

How the horizontal Pacific slab subducted over such a long distance inland has been unclear (Goes et al., 2017). Geodynamic models confirmed that a reasonable trench-retreat history (Figure S2) with both a viscosity jump and phase change across the 660-km discontinuity prevented the slabs from immediately sinking into the lower mantle (cases 1-1 to 1-6). We also note a broad northwestward flow beneath East Asia during the Neogene is predicted by all the cases. We suggest that the global-scale flow in the ambient mantle should not be neglected in terms of the formation of horizontal slabs, although lateral mantle flow may have been exaggerated in the present kinematic models. Additionally, our modeling recognized major segmentation in the horizontal slabs. We believe that this segmentation would also affect the slab-lying process. Finally, it is suggested that the negative buoyancy exerted by the Izanagi slab triggered local downwelling beneath East Asia, which could have pulled the horizontal Pacific slab into the lower mantle at its tip, resulting in its partial penetration (Figure 4).

5. Conclusions

This study's 4-D forward models of plate-mantle systems confirmed that the reconstruction of the NE migration of a TTT triple junction since 30 Ma fits with both geological evidence and geophysical observations. The consistency between the modeling results and the deep-mantle structure interpreted from seismic tomography images demonstrates the predictability of the space-time evolution of the plate-mantle system. Additionally, the triple junction's migration led to the overlapping, tearing, detachment, and deformation of subducted slabs beneath East Asia. The Pacific slab, which was subducted horizontally and stagnated above the 660-km discontinuity, was induced by a combination of trench retreat, large-scale mantle flow, and radial viscosity jumps and phase relationships that characterized the mantle transition zone. Long-term Izanagi subduction created substantial thermal anomalies in the lower mantle, whose negative buoyancy drove large-scale westward mantle flow, thus shaping the stagnant slab morphology.

Acknowledgments
L. S. F., M. P. F., and Z. B. acknowledge the funding from the Strategic Priority Research Program (B) of the Chinese Academy of Sciences (grant XDB18000000), National Key R&D Plan (grant 2017YFC0601405), and Natural Science Foundation of China (41820104004, 91114203, and 41572189). M. G. was supported by the National Science Foundation (EAR-1645775). Figures 1–4 were prepared by using the Generic Mapping Tools program (Wessel & Smith, 1998). We thank D. Bower for valuable discussion on data assimilation, W. Leng and T. Yang for their assistance with CitcomS, and S. Zahirovic and D. Müller for generously sharing software for seafloor age grids. We also thank J. Ritsema, S. Honda, and an anonymous reviewer for their very detailed reviews and constructive comments. The data making up the model cross sections used here have been deposited in the Caltech Data Repository (https://data.caltech.edu/records/1237) and assigned DOI: 10.22002/D1.1237. https://data.caltech.edu/ More detailed information of tectonic events sequence and method can be found in the supporting information.

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